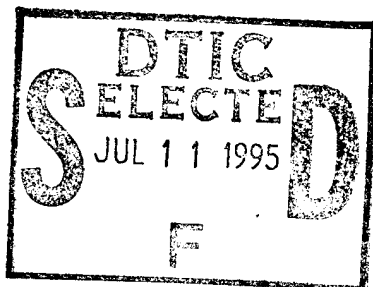


TECHNICAL REPORT

**VALIDATION OF MATHEMATICAL MODELS FOR PREDICTING PHYSIOLOGICAL
EVENTS DURING WORK AND HEAT STRESS**

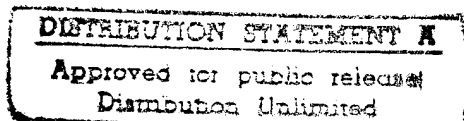


by

Kenneth K. Kraning, II

June, 1995

Biophysics and Biomedical Modeling Division
U.S. Army Research Institute of Environmental Medicine
Natick, MA 01760-5007



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EXECUTIVE SUMMARY

To estimate safe exposure times, computerized biophysical models of temperature regulation are used to forecast physiological responses under different working conditions and environmental conditions and with different clothing ensembles. The purposes of this study were to (1) review the designs of three models in use at USARIEM, (2) determine their usefulness under different conditions using data from a variety of heat stress studies, (3) identify possible sources of error, (4) suggest improvements to extant models, and (5) recommend directions for further research and additional modeling efforts. The mathematical models evaluated in this report are (a) The USARIEM Heat Strain Model (ARIEM), (b) The John B. Pierce Foundation Two-Node Thermoregulatory Model (PIERCE) and (c) SCENARIO, a six-node representation of thermoregulation. Thermoregulatory simulations like PIERCE and SCENARIO operate in the time domain, algebraically summing incremental changes over time, while ARIEM is analytic, making a single calculation of final rectal temperature and estimating intermediate values with an exponential function of time.

To substantiate various modeling approaches, data were obtained from recent appropriate studies for which detailed time-series data were available. A summary statistic termed "the root mean squared deviation (rmsd)" was used to compare experimental values with those obtained with the models. Based on these data, the performance of SCENARIO surpassed the performance of the other two models.

Potential sources of error in the three models are discussed, including those arising from estimating the following: heat production, the state of acclimation, the distribution of peripheral blood flow, and the cardiac stroke volume.

This analysis points to needs for future research and modeling in the following areas: gender differences, physiological correlates of psychological measures of performance, and heat stress data from work not involving locomotion, but instead, work of long duration and ordinary daily work, including the effects of nutrition and hydration.

INTRODUCTION

Protective clothing can readily convert a tolerable long-term working condition into a situation in which exposure time is limited by rapidly accumulating heat strain (Kraning and Gonzalez, 1991). It is a challenge to produce simple and universal exposure guidelines for those administering activities of personnel because effects of different clothing types, workloads and environmental conditions on the expected physiological responses are complex. To reduce uncertainties in estimating safe exposure times, computerized biophysical models of temperature regulation are used to forecast physiological responses under different working and environmental conditions, and with different clothing ensembles. Extant models emphasize prediction of body core temperature; expected heat casualty rates are assigned to specific levels of body temperature and then the models are used to forecast the time to reach these specific levels.

The purposes of this document are to (1) review the designs of three models in use at USARIEM, (2) determine their usefulness under different conditions using data from a variety of heat stress studies, (3) identify possible sources of error, (4) suggest improvements to extant models, and (5) recommend directions for further research and additional modeling efforts.

MODELING APPROACHES

The simplest modeling approach is to attempt a direct empirical correlation between tolerance time and independent variables describing the thermal environment and the work. This tactic was taken by Bell and colleagues (1971). Using a statistical approach, they found that the relationship between the time of imminent collapse of 87 fit young male volunteers exercising at a single workload and a hybrid variable composed of weighted dry bulb and psychrometric wet bulb temperatures was roughly hyperbolic. Using this hyperbolic model they compiled tables of exposure times that would protect 75%, 90%, 95% or 99% of their volunteers from imminent collapse.

There are several difficulties with an approach as general as this. First, no particular scheme of weighting dry and wet bulb temperatures is universally appropriate in all situations. Second, dry and wet bulb temperatures are not truly independent measures; wet bulb temperature increases and decreases with dry bulb temperature as well as with humidity. To be an index of only humidity, the wet bulb depression must be used. Third, while this regression may describe the specific conditions of the experiment, the introduction of differing workloads and clothing would require completely new studies and analyses. Fourth, these environmental variables are only indirectly related to the actual causes of collapse, which are physiological.

A more sophisticated method is to identify values of measurable physiological variables that herald impending heat illness and then devise mathematical functions to predict the time course of change in these variables (collectively referred to as "heat strain") under different degrees of heat stress, i.e. (different thermal environments, working at different rates and wearing various clothing ensembles). There is less than unanimous agreement not only on what these critical values are but also on what variables define strain. Candidate variables include the level and/or rate of rise in internal or core temperature (T_c) measured either in the esophagus or the rectum, heart rate (HR), skin temperature (T_{sk}), the rate of body heat storage (S) and the convergence of T_c and T_{sk} (Iampietro, 1971; Pandolf and Goldman, 1978).

There are two main classes of mathematical models that are used to predict heat strain: data regression models and bioengineering simulations. A data regression paradigm represents one response variable and, for any given set of conditions, predicts a single value for that variable. Model development usually starts with basic assumptions about the independent variables and the mathematical form of the predictive equation and then relies on a database to optimize equation parameters.

A bioengineering simulation, on the other hand, is mechanistic; a mathematical analog of body heat exchanges and physiological processes. Equations are written to describe heat flow between and temperature levels within body compartments (the

"passive" system), and mathematical algorithms are constructed to emulate regulated physiological responses to changes in body temperature (the "active" system); the active system attempts to control heat flow and temperatures within the passive system (Kraning, 1991). A large database is not required as a basis for a simulation. What is required are quantitative studies that have investigated the underlying physiological mechanisms upon which control algorithms can be modeled.

MODELS CONSIDERED IN THIS REPORT

The mathematical models designated for evaluation in this report are (a) The USARIEM Heat Strain Model (ARIEM), (b) The John B. Pierce Foundation Two-Node Thermoregulatory Model (PIERCE) and (c) SCENARIO, a Six-Node Representation of Thermoregulation.

THE USARIEM HEAT STRAIN MODEL (ARIEM)

ARIEM is a collection of three regression models to predict final equilibrium T_{re} (T_{ref}), final HR and final sweating rate (m_{sw}) for different combinations of work (by walking), environmental heat stress and clothing types. The equations for predicting T_{ref} and HR were published in Givoni and Goldman, 1972 and Givoni and Goldman, 1973, respectively, while the equation for m_{sw} was published by Shapiro et al., 1982. The regression model for predicting T_{ref} correctly assumes that for any combination of heat production, environmental heat load and clothing there exists a hypothetical steady-state combination of internal and skin temperatures that will allow full dissipation of metabolic heat as fast as it is generated.

The form of the general predictive equation for T_{ref} is:

$$T_{ref} = T_0 + a(M_{net}) + b(H_{r+c}) + c(\exp d[E_{req} - E_{max}]) \quad (Eq. 1)$$

where T_0 is the initial value for T_{re} , M_{net} and H_{r+c} are the metabolic and environmental heat loads, respectively, $(E_{req} - E_{max})$ is the difference between the evaporation rate required to achieve thermal balance and the maximum evaporative capacity of the

environment (W.m^{-2}) and a, b, c, d are empirical coefficients derived from regression analysis of a database.

Once calculated, T_{ref} is used to predict the time course of rectal temperature. T_{sk} is treated as a constant independent variable, usually set at 36°C ; the skin surface is always considered completely wetted; and the vapor pressure of water on the skin surface (P_{sk}) is always 44 torr. E_{req} (in W) is obtained from the heat balance equation:

$$E_{req} = M_{net} + (11.6/clo)(T_a - 36) \quad (\text{Eq. 2})$$

where M_{net} is heat production (W), clo is the total insulation of the clothing system (ND) and T_a is the ambient temperature ($^\circ \text{C}$). E_{max} (in W) is obtained from:

$$E_{max} = 25.5(i_m/clo)(44 - f_a P_a) \quad (\text{Eq. 3})$$

where i_m is the permeability index of the clothing system (nd), f_a is the ambient relative humidity (%) and P_a is the saturation vapor pressure of H_2O (Torr) at the prevailing ambient temperature.

To predict the time course of change from T_0 to T_{ref} , Givoni formulated three empirical expressions (Givoni and Goldman, 1972). 1) At rest under heat stress:

$$T_{re}(t) = T_0 + (T_{ref} - T_0) (0.1) \exp(0.4^{(t-0.5)}), \quad (\text{Eq. 4a})$$

where $T_{re}(t)$ is rectal temperature at time t (hrs). 2) During work under heat stress:

$$T_{re}(t) = T_0 + (T_{ref} - T_0)(1 - \exp[-2 - 0.5\{T_{ref} - T_0\}][t - 58/M]), \quad (\text{Eq. 4b})$$

where M is the rate of heat production in W.m^{-2} . 3) During recovery from work under heat stress:

$$T_{re}(t) = T_w - (T_w - T_{rst})(1 - \exp[-\{t - t_{lag}\}]) \quad (\text{Eq. 4c})$$

where $T_w = T_{re}$ at the beginning of decrease, $T_{rst} = \text{equilibrium resting } T_{re} = 1.5 (1 - \exp[-1.5 CP_{eff}])$, and $t_{lag} = 0.25 \exp(-0.5 CP_{eff})$. CP_{eff} is termed the "effective cooling power".

$$CP_{eff} = 0.27 (i_m/clo) (44 - P_a) + (0.174/clo) (36 - T_a) - 1.57. \quad (\text{Eq. 5})$$

Although heart rate predictive equations were proposed by Givoni, they are not used in the present ARIEM Heat Strain Model. His heart rate (HR) predictive equation draws upon the same variables as the rectal temperature equation.⁸ First, he calculates an "Index of Heart Rate" (I_{HR}) having a zero origin:

$$I_{HR} = 0.4 M + (2.5/clo)(T_a - 46) + 80 \exp(0.0047 [E_{req} - E_{max}]). \quad (\text{Eq. 6})$$

From I_{HR} , final equilibrium heart rate (HR_f) is obtained from one of two predictive formulas:

$$R_f = 65 + 0.35 (I_{HR} - 25); \text{ for } 0 < I_{HR} < 225 \quad (\text{Eq. 7a})$$

or

$$HR_f = 135 + 42(1 - \exp[-I_{HR} - 225]); \text{ for } I_{HR} \geq 225. \quad (\text{Eq. 7b})$$

Givoni then approximates the change in heart rate in three separate equations.

1) At rest under heat stress:

$$HR(t) = 65 + (HR_f - 65)(1 - \exp[-3t]). \quad (\text{Eq. 8a})$$

2) During work under heat stress:

$$HR(t) = 65 + (HR_f - 65)(1 - 0.8\exp[-6 - 0.03\{HR_f - 65\}t]). \quad (\text{Eq. 8b})$$

3) During recovery from work:

$$HR(t) = HR_w - (HR_w - HR_r)\exp[-kbt], \quad (\text{Eq. 8c})$$

where HR_w = heart rate at end of work period, HR_r = resting heart rate in the given environment (from 7a or 7b), $k = 2 - 0.1(HR_w - HR_r)$, and $b = 2.0 + 12(1 - \exp[-0.3CP_{eff}])$.

The empirical sweat loss prediction equation authored by Shapiro *and associates*, 1982, was designed to forecast water requirements for military personnel losing fluid in sweat. The evaporative equivalent of the rate of sweat loss, m_{sw} in $W \cdot m^{-2}$, is given by:

$$m_{sw} = 18.7(E_{req})(E_{max})^{-0.455} \quad (\text{Eq. 9})$$

for

$$50 < E_{req} < 360 \text{ and } 20 < E_{max} < 525.$$

THE PIERCE FOUNDATION TWO-NODE THERMOREGULATORY MODEL (PIERCE)

PIERCE is a bioengineering-type simulation of thermoregulation developed by Gagge et al. as part of a "New Effective Temperature Scale" or "Comfort-Health Index" (Gagge *et al.*, 1971; Gagge, 1973). Thermoregulatory simulations like PIERCE and SCENARIO operate in the time domain, algebraically summing incremental changes over time, while ARIEM is analytic, making a single calculation of final rectal temperature then interpolating intermediate values as an exponential function of time.

PIERCE was derived from the more general Stolwijk & Hardy 24-node model also previously developed at the John B. Pierce Foundation for semi-nude volunteers (Stolwijk and Hardy, 1966). Although PIERCE was designed primarily as a tool for assessing the comfortableness of buildings by simulating the thermal responses of normally clothed sedentary individuals in a uniformly heated and normally ventilated environment, the authors claim that it can also be applied to many levels of activity, various air movements and clothing types, and to radiant heating and cooling. It consists of a passive or controlled system that models the body as a single cylinder of fixed dimensions containing two compartments: an inner core and an outer shell. It has an active or controlling system that is in a negative feedback control loop with the passive system. This control system regulates heat production in the core, heat flow between core and shell by conduction and by convective blood flow transport, and evaporative heat loss by regulating sweat secretion onto the shell (skin) surface. An outer clothing layer modifies heat exchange between the skin surface and the environment. Unlike ARIEM, PIERCE and SCENARIO do not assume a fixed T_{sk} or P_{sk} or that the skin surface is always 100% wet. In PIERCE, as in all bioengineering-type simulations of thermoregulation, predicted variables are intrinsically functions of time, so that empirical curve-fitting from an initial to a final value is not necessary. PIERCE's dynamic outputs include core temperature, $T_{cr}(t)$; skin temperature, $T_{sk}(t)$; and the rate of sweating $m_{sw}(t)$ and heat production from shivering (M_{sh}), plus changes in any calculated variables (e.g., E_{req} , E_{max}) whose values would depend on the value of these primary variables. PIERCE does not have a cardiovascular system, and $HR(t)$ is not an output variable.

PIERCE's algorithms for regulating blood (heat) flow between core and shell, sweating rate and shivering are controlled through feedback signals generated by deviations in temperatures of the core and shell from their respective set-points (sT_{cr} , sT_{sk}) :

$$CrSig(t) = T_{cr}(t) - sT_{cr} \quad (Eq. 10a)$$

and

$$SkSig(t) = T_{sk}(t) - sT_{sk} \quad (Eq. 10b)$$

The model assumes that these control signals arise from sets of afferent thermal sensors for cold and warmth residing in both core ($CldCrSig$, $WrmCrSig$) and skin ($CldSkSig$, $WrmSkSig$) compartments. It is further assumed that their outputs cannot be negative and only one of each set can be active at a time. So, for example, if $CrSig(t)$ is equal to or less than zero, then $CldCrSig$ is set equal to $|CrSig(t)|$ and $WrmCrSig$ is set equal to zero. On the other hand, if $CrSig(t)$ is greater than zero, then $WrmCrSig$ is set equal to $|CrSig(t)|$ and $CldCrSig$ is set equal to zero. The same reasoning is applied to control signals arising from skin temperature.

The PIERCE skin blood flow algorithm, adapted from Stolwijk & Hardy,¹⁴ assumes that vasodilation arises from activity of warm thermoreceptors in the core and that vasoconstriction arises from activity of cold thermoreceptors in the skin. Thus, at any time:

$$Dilate(t) = (3.34)WrmCrSig(t) \quad (Eq. 11a)$$

and

$$Constrict(t) = (0.1)CldSkSig(t) \quad (Eq. 11b)$$

The level of skin blood flow ($l \cdot \min^{-1}$) is determined by interaction of drives for vasodilation and vasoconstriction:

$$SkBF(t) = A_{Du}[0.105 + Dilate(t)]/[1 + Constrict(t)], \quad (Eq. 11c)$$

where A_{Du} is the Dubois body surface area.

Effective shell thickness is a variable, increasing with vasoconstriction and narrowing with vasodilation. The fraction of body mass in the shell at any time is given by:

$$\alpha(t) = 0.0442 + (0.3509/[60\{SkBF(t)/A_{Du}\} - 0.01386]), \quad (Eq. 12)$$

and the fraction of body mass in the core is given by: $[1 - \alpha(t)]$.

The algorithm for controlling m_{sw} ($\text{g} \cdot \text{min}^{-1}$) uses these proportions to weight the influence of core and skin signals:

$$m_{sw}(t) = [4.17A_{Du}][\alpha(t)SkSig(t) + \{1 - \alpha(t)\}CrSig(t)]\exp[SkSig(t)/10]. \quad (\text{Eq. 13})$$

The change in the rate of core heat production due to shivering (W) is a multiplicative function:

$$M_{sh}(t) = 19.4[CldSkSig(t)][CldCrSig(t)]. \quad (\text{Eq. 14})$$

Heat is being produced in the core (M_{net}), exchanged by direct conduction and by vascular transport with the shell, lost from the core via the respiratory passages (C_{res} , E_{res}) and lost from the shell through the clothing to the environment (C_{sk} , R_{sk} , E_{sk}). The rates of change in heat content of these two compartments (dQ_{cr}/dt , dQ_{sh}/dt) are given by:

$$\frac{dQ_{cr}}{dt} = [M_{net}(t) - E_{res}(t) - C_{res}(t)] - [K \cdot \Delta T_{cs}(t)] - [C_{bl} \cdot SkBF(t) \cdot \Delta T_{cs}(t)] \quad (\text{Eq. 15a})$$

and

$$\frac{dQ_{sk}}{dt} = [K \cdot \Delta T_{cs}(t)] + [C_{bl} \cdot SkBF(t) \cdot \Delta T_{cs}(t)] - [R_{sk}(t) + C_{sk}(t)] - [E_{sk}(t)] \quad (\text{Eq. 15b})$$

where $\Delta T_{cs}(t) = T_{cr}(t) - T_{sk}(t)$, K is the conductance between core and shell (in $\text{W} \cdot \text{C}^{-1}$), C_{bl} is the heat capacity of blood (in $\text{W} \cdot \text{min}^{-1} \cdot \text{C}^{-1}$), and $R_{sk}(t)$, $C_{sk}(t)$, and $E_{sk}(t)$ are the rates of surface heat loss by radiation, convection and evaporation, respectively.

Integration of Eqs. 15a,b gives the quantity of heat gained or lost in each compartment:

$$Q_{cr} = \int \frac{dQ_{cr}}{dt} \cdot dt \quad (\text{Eq. 16a}) \quad \text{and} \quad Q_{sh} = \int \frac{dQ_{sk}}{dt} \cdot dt. \quad (\text{Eq. 16b})$$

Integration is approximated by substitution of a very small finite value Δt for dt . Then, using Equations 17a and 17b:

$$\Delta Q_{cr} \approx \frac{dQ_{cr}}{dt} \cdot \Delta t \quad (\text{Eq. 17a}) \quad \text{and} \quad \Delta Q_{sh} \approx \frac{dQ_{sk}}{dt} \cdot \Delta t. \quad (\text{Eq. 17b})$$

The temperature change of core (T_{cr}) and shell (T_{sh}) during period t is given by:

$$\Delta T_{cr} = \frac{\Delta Q_{cr}}{C_{cr}} \quad (\text{Eq. 18a}) \quad \text{and} \quad \Delta T_{sh} = \frac{\Delta Q_{sk}}{C_{sk}}. \quad (\text{Eq. 18b})$$

where the heat capacity of the shell is $C_{sh} = (a)(C_{bdy})(BW)$, and the heat capacity of the core is $C_{cr} = (1 - a)(C_{bdy})(BW)$. Then, at any time t_i , the temperature of core and shell (skin) compartments can be found from:

$$T_{cr}(t_i) = T_{cr0} + \sum_{k=1}^{i-1} \Delta T_{cr}(k) \quad (\text{Eq. 19a}) \quad \text{and} \quad T_{sh}(t_i) = T_{sh0} + \sum_{k=1}^{i-1} \Delta T_{sh}(k), \quad (\text{Eq. 19b})$$

where $i = \frac{t_i}{\Delta t} + 1$; T_{cr0} and T_{sh0} are initial temperature conditions.

This completes the computational loop. With each new calculation of $SkBF$, m_{sw} and M_{sh} , new values of T_{cr} and T_{sh} are calculated; these are then used to calculate once again new values for $SkBF$, m_{sw} and M_{sh} at time $t_1 + \Delta t$.

A SIX-NODE REPRESENTATION OF HUMAN THERMOREGULATION (SCENARIO)

SCENARIO is also a single-cylinder representation of the human body, but unlike PIERCE, it contains five concentric annular compartments and an inter-connecting central blood compartment (Figure 1). SCENARIO was specifically designed to be a tool in heat strain prediction. Compartment dimensions and inter-compartment

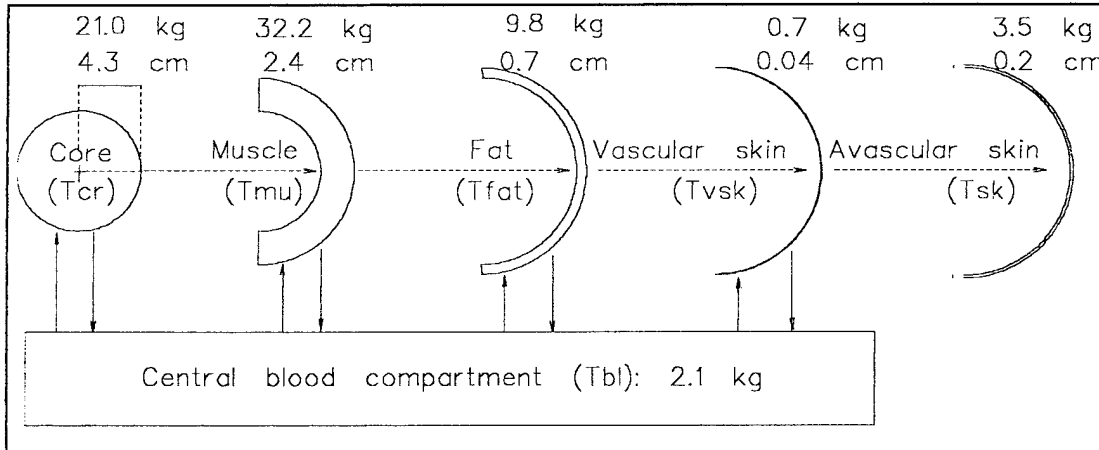


Figure 1. Cross section of cylindrical model containing five concentric annular tissue compartments. Dimensions are for an individual with $W = 70$ kg, $A_b = 1.8$ m².

conductance's are not fixed, but are calculated as a function of the subject's height, weight and percent body fat (Kraning, 1991). SCENARIO has a primitive flow-controlled cardiovascular system for the sole purpose of managing heat convection among compartments and of transporting O_2 to skeletal muscle.

The two equations describing the rate of change in heat content in core and shell of PIERCE (15a and 15b) are replaced in SCENARIO by six equations for the core, muscle, fat, vascular skin, non-vascular skin, and for the central blood compartment which must be solved together:

Core Compartment: (Eq. 20a)

$$\frac{d}{dt} Q_{cr}(t) = H_{cr}(t) - \{k_{cr,mu}[T_{cr}(t) - T_{mu}(t)]\} - \{BF_{cr}(t) \cdot \rho_{bl} \cdot C_{bl}[T_{cr}(t) - T_{bl}(t)]\}$$

Muscle Compartment: (Eq. 20b)

$$\frac{d}{dt} Q_{mu}(t) = H_{mu}(t) + \{k_{cr,mu}[T_{cr}(t) - T_{mu}(t)]\} - \{k_{mu,fat}[T_{mu}(t) - T_{fat}(t)]\} - \{BF_{mu}(t) \cdot \rho_{bl} \cdot C_{bl}[T_{mu}(t) - T_{bl}(t)]\}$$

Fat Compartment: (Eq. 20c)

$$\frac{d}{dt} Q_{fat}(t) = H_{fat}(t) + \{k_{mu,fat}[T_{mu}(t) - T_{fat}(t)]\} - \{k_{fat,vsk}[T_{fat}(t) - T_{vsk}(t)]\} - \{BF_{fat}(t) \cdot \rho_{bl} \cdot C_{bl}[T_{fat}(t) - T_{bl}(t)]\}$$

Vascular Skin Compartment: (Eq. 20d)

$$\frac{d}{dt} Q_{vsk}(t) = H_{vsk}(t) + \{k_{fat,vsk}[T_{fat}(t) - T_{vsk}(t)]\} - \{k_{vsk,sk}[T_{vsk}(t) - T_{sk}(t)]\} - \{BF_{vsk}(t) \cdot \rho_{bl} \cdot C_{bl}[T_{vsk}(t) - T_{bl}(t)]\}$$

Skin Surface Compartment: (Eq. 20e)

$$\frac{d}{dt} Q_{sk}(t) = H_{sk}(t) + \{k_{vsk,sk}[T_{vsk}(t) - T_{sk}(t)]\} - \{A_D[(R+C)+E]\}$$

Blood Compartment: (Eq. 20f)

$$\begin{aligned} \frac{d}{dt} Q_{bl}(t) = & \rho_{bl} \cdot C_{bl} \{ [T_{cr}(t) - T_{bl}(t)]BF_{cr}(t) \} + \rho_{bl} \cdot C_{bl} \{ [T_{mu}(t) - T_{bl}(t)]BF_{mu}(t) \} + \dots \\ & \dots + \rho_{bl} \cdot C_{bl} \{ [T_{fat}(t) - T_{bl}(t)]BF_{fat}(t) \} + \rho_{bl} \cdot C_{bl} \{ [T_{vsk}(t) - T_{bl}(t)]BF_{vsk}(t) \} - \{C_{res}(t) + E_{res}(t)\} \end{aligned}$$

The form of solution to this equation set is similar to Eqs. 16a,b through Eqs. 19a,b. Cardiac stroke volume (SV) is a controlled variable influenced by work load, posture and skin temperature. Temperatures of all compartments (T_{cr} , T_{mu} , T_{fat} , T_{vsk} , T_{sk} and T_{bl}), blood flows to four compartments ($SkBF$, $MuBF$, $FatBF$, $CrBF$) as well as m_{sw} , HR, SV, cardiac output (CO) and state of hydration are

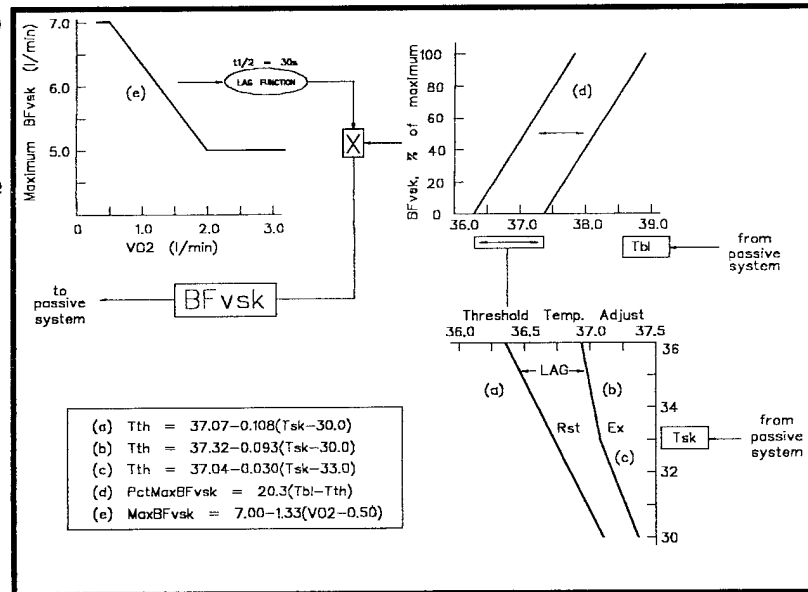


Figure 2. Algorithm for calculating BF_{vsk} as a function of T_{bl} . Maximum BF_{vsk} is determined by activity level (Eq. e), zero-point by activity level and T_{sk} .

continuously available as outputs. The control algorithms for controlling m_{sw} and Msk are essentially the same as in PIERCE. However, the algorithms for controlling $SkBF$, $MuBF$, and $CrBF$ are completely different. Conductance between vascular and non-vascular skin layers and the level of cardiac stroke volume are also controlled by novel feedback algorithms. (The details of these will not be presented here; for this the reader is directed to: Kraning, 1991.) A diagram representing the algorithm for $SkBF$ is shown as an example in Figure 2.

Heat is produced by all of the compartments in proportion to their mass, but only the muscle compartment increases its heat production with changes in activity level or shivering. Heat is exchanged by conduction between adjacent compartments; all compartments except the surface nonvascular skin layer exchange heat with the central blood compartment by vascular convection. Respiratory heat losses affect the central blood compartment directly, rather than the core compartment. The transfer of heat from the skin surface through the clothing to the environment is almost identical to the scheme in PIERCE.

COMPUTER IMPLEMENTATION OF MATHEMATICAL MODELS

THE ARIEM MODEL

The official version of the USARIEM Heat Strain Model, the "P²NBC² Heat Strain Decision Aide", was used in this study. This version was written in ADA by Science Applications International.

THE PIERCE MODEL

An IBM PC version of PIERCE written in FORTRAN has been obtained from its principal author, Dr. A. Pharo Gagge of the John B. Pierce Foundation, New Haven, CT. For the present study PIERCE was rewritten in TurboBasic to make input/output options similar to and comparable with SCENARIO's input/output options. PIERCE outputs are the time course of changes in core temperature, skin temperature and sweating rate. Data on heat production, environment and clothing can be input and changed at anytime during the work period.

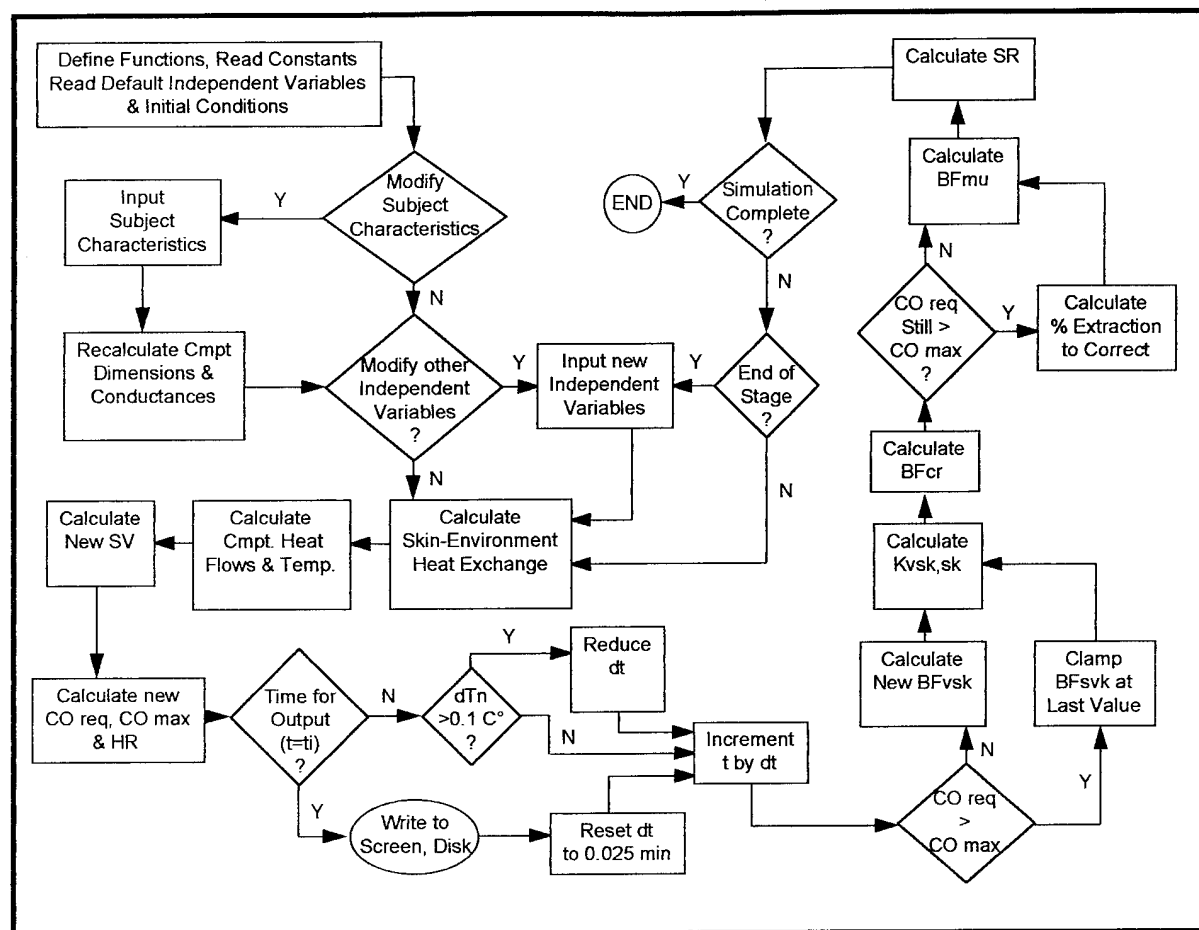


Figure 3. Flow chart of main program elements in SCENARIO engine. Nominal iteration rate is $40 \times \text{min}^{-1}$.

THE SCENARIO MODEL

SCENARIO is implemented for the IBM PC. The source code is in TurboBasic which allows flexible and easily modified input/output options. Heat production, environmental and clothing data can be either continuous or cycles. SCENARIO outputs include the time course of changes in heart rate, cardiac stroke volume, skin temperature core temperature, hydration state and sweating rate. A flow diagram of the SCENARIO program is shown in Figure 3.

EVALUATION OF MODEL PERFORMANCE

In order to substantiate various models and modeling approaches, data were obtained from recent appropriate studies performed here at USARIEM for which detailed

time-series data were available and entered into the P²NBC² - USARIEM database as well as a certain relevant studies captured from the open literature (Kraning, 1991). Graphical comparisons are useful and necessary for identifying qualitative problems such as tracking errors or consistent underprediction or overprediction; qualitative analysis may be the only way to reveal conceptual flaws in a model design. For quantitative evaluation of how well model outputs agree with experimental observations, a statistical instrument is needed. Haslam and Parsons have developed such an instrument, a summary statistic designated "the root mean squared deviation (rmsd)", to compare values obtained from models with experimental values at corresponding time points (Haslam and Parsons, 1988).

$$rmsd = \sqrt{\frac{1}{n} \sum_{i=1}^n d_i^2} \quad (\text{Eq. 21})$$

where d_i = difference between observed and predicted values at each time point, and n = the number of time points. The units of the rmsd are the same as those of the variable; therefore, values of the rmsd can be compared directly with the standard deviation (sd) of the data set. The ultimate goal is to improve model performance so that the variance between data mean and model output is no larger than the sd of the data sets, and to maintain this precision over a wide variety of working, environmental and clothing conditions. Used judiciously, in conjunction with qualitative graphical methods, comparison of the rmsd. and sd metrics is a useful, quantitative strategy for evaluating model performance under a wide variety of conditions.

Model evaluation in this report is based on data from studies recently completed at USARIEM that have been prepared for entry into the P²NBC² - USARIEM database, as well as one well-described study in the open literature. These studies are described individually below.

KRANING AND GONZALEZ, 1991

Four volunteers walked on a treadmill (1.34 m.s⁻¹, 3% grade) in a warm environment (30°C, 25% RH) while wearing shorts and tee-shirts or a heavy, semi-permeable protective clothing ensemble (BDU + BDO in MOPP 4 configuration). Data for T_{re} , T_{sk} and HR were averaged across volunteers at 15s intervals. These data, along with error

statistics, are available for comparison with model outputs at corresponding time points. This data set illustrates the different physiological patterns resulting from exposure to mild, fully compensable heat stress and severe uncompensable heat stress.

When only shorts and tee-shirts were worn, heat stress was mild and fully compensable; all volunteers achieved a steady state (Figure 4). Under these conditions both PIERCE and SCENARIO tracked the data reasonably well, although PIERCE showed better agreement during the first 15 min and SCENARIO demonstrated better agreement during the last 30 min. ARIEM did not track

the data well and, by 75 minutes, over-predicted observed T_{re} by 1.0°C . The ave sd of this data set was $\pm 0.17^{\circ}\text{C}$ and the ave rmsd's for SCENARIO, PIERCE and ARIEM were $\pm 0.19^{\circ}\text{C}$, $\pm 0.11^{\circ}\text{C}$ and $\pm 0.39^{\circ}\text{C}$, respectively. This data set reinforces the importance of visual inspection in addition to calculating an overall summary statistic.

Figure 5 shows data from the same subjects under the same conditions but wearing MOPP4, making heat stress severe and uncompensable. Under these conditions SCENARIO best represented the data set while both PIERCE and ARIEM progressively deviated from the data set. The ave data set

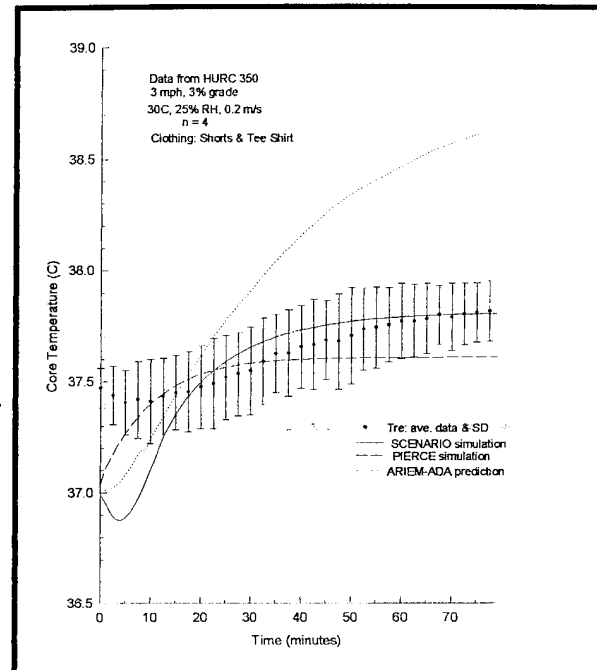


Figure 4. Four unacclimated subjects in shorts exercised in mild compensable heat stress. Figure compares data mean and sd with model outputs. PIERCE and SCENARIO showed reasonable agreement with data.

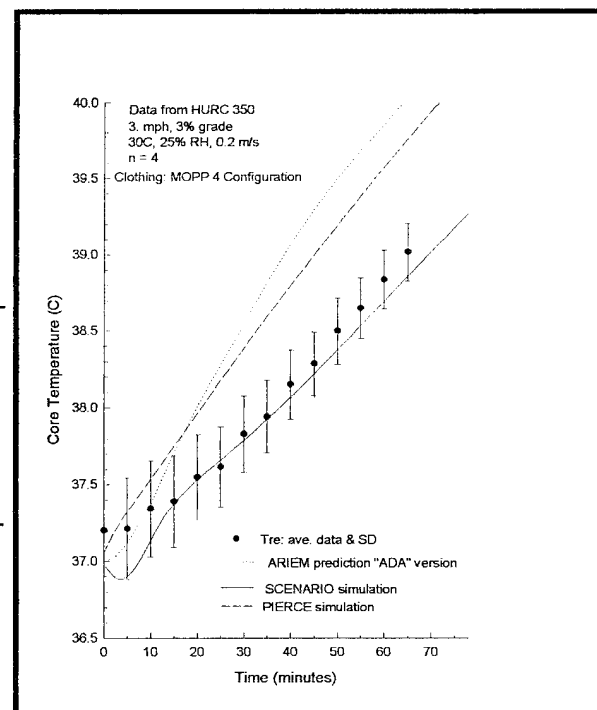


Figure 5. The same four subjects in BDU+ BDO exercising at the same rate under the same conditions. Heat stress was uncompensable. Both PIERCE & ARIEM exaggerated the rate of core temperature rise.

sd was $\pm 0.23^{\circ}\text{C}$ and the average rmsd's for SCENARIO, PIERCE and ARIEM were $\pm 0.27^{\circ}\text{C}$, $\pm 0.69^{\circ}\text{C}$ and $\pm 0.76^{\circ}\text{C}$, respectively.

PANDOLF AND ASSOCIATES, 1992

Ten volunteers wearing shorts rested for 10 min in a hot, dry environment (49°C , 20% RH), then worked in the same environment on a stationary ergometer at a workload requiring 53% VO_2max for 50 min. Data for T_{es} and T_{sk} were averaged across volunteers at 15 s intervals. Data for HR were taken at 10 min intervals. Averaged data for this experiment, along with error statistics, are available for comparison with model outputs at corresponding time points (Figure 6). In this instance ARIEM best represented the data set, and PIERCE

showed the greatest departure from the data time course. The ave sd of the data set was $\pm 0.25^{\circ}\text{C}$ while the ave rmsd's for SCENARIO, PIERCE and ARIEM were $\pm 0.27^{\circ}\text{C}$, $\pm 0.69^{\circ}\text{C}$, and $\pm 0.09^{\circ}\text{C}$, respectively.

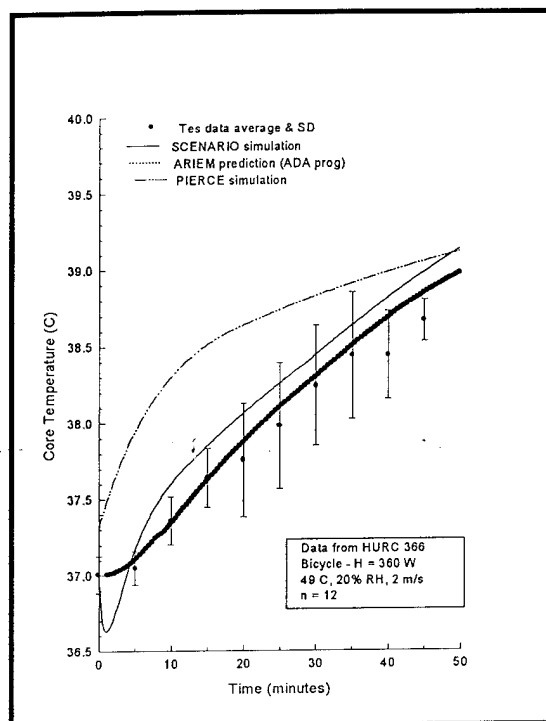


Figure 6. Twelve fully acclimated volunteers clad only in shorts pedaled at 360 W in a hot dry environment. ARIEM gave the best fit to data. PIERCE overpredicted core temperature rise for 30 min, but tended to converge at later times.

GONZALEZ AND COLLEAGUES, 1978

Five volunteers clothed in shorts exercised in 16 experiments on a bicycle ergometer working at 28% VO_2max . In each experiment volunteers were exposed to a different combination of temperature and humidity chosen so as to produce one of six different effective temperature states. Experiment-end (40 minutes) tabulated data for T_{es} , T_{sk} and HR from these 16 experiments, averaged across volunteers along with error statistics, have been published. Here they are compared with model outputs. Results are shown in Figure 7. Both SCENARIO and PIERCE provided reasonable agreement over the 15 environments, although PIERCE was somewhat better than

SCENARIO at lower stress levels and SCENARIO was better than PIERCE at high levels of stress. For SCENARIO and PIERCE there were no consistent patterns of under or over prediction. ARIEM consistently over-predicted in all 15 environments. The ave sd of the data set was $\pm 0.15^{\circ}\text{C}$ while the ave rmsds for SCENARIO, PIERCE and ARIEM were $\pm 0.17^{\circ}\text{C}$, $\pm 0.22^{\circ}\text{C}$, and $\pm 0.63^{\circ}\text{C}$, respectively.

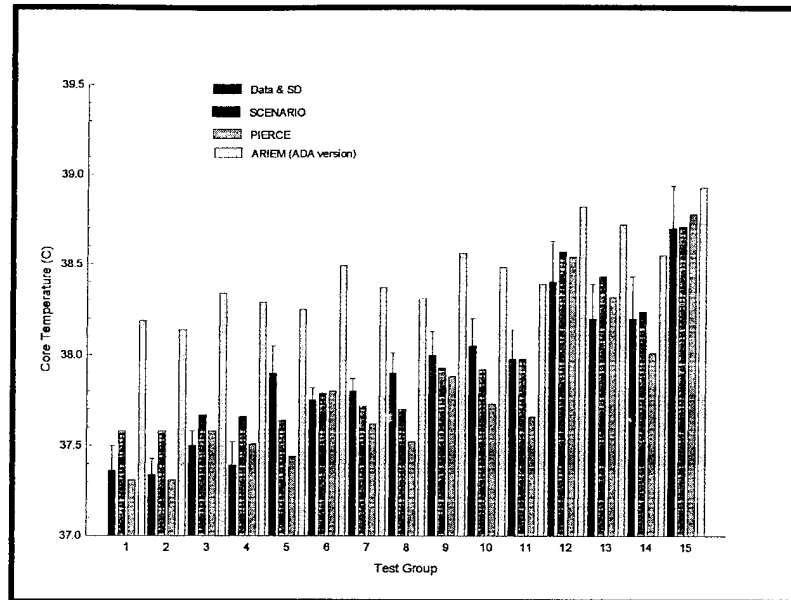


Figure 7. Data from 15 experiments of Gonzalez et al., 1978. Average of 5 subjects at the end of 40 min of work at 410 W.

GONZALEZ AND ASSOCIATES, 1992

Fourteen volunteers clothed in a standard 90-mil chemical protective overgarment integrated with a prototype 70-mil permeable hood first rested for 20 min in a 35°C DB, 50% RH environment then performed steady treadmill exercise ($1.4\text{ m}\cdot\text{s}^{-1}$) for 70 min. Air movement was maintained at $5\text{ m}\cdot\text{s}^{-1}$. The ave sd of the data set was $\pm 0.14^{\circ}\text{C}$, while the ave rmsds for SCENARIO, PIERCE and ARIEM were $\pm 0.21^{\circ}\text{C}$, $\pm 0.26^{\circ}\text{C}$, and $\pm 0.50^{\circ}\text{C}$, respectively. Data are compared with model outputs in Figure 8. Again, PIERCE was somewhat better than SCENARIO during the initial 20 min resting

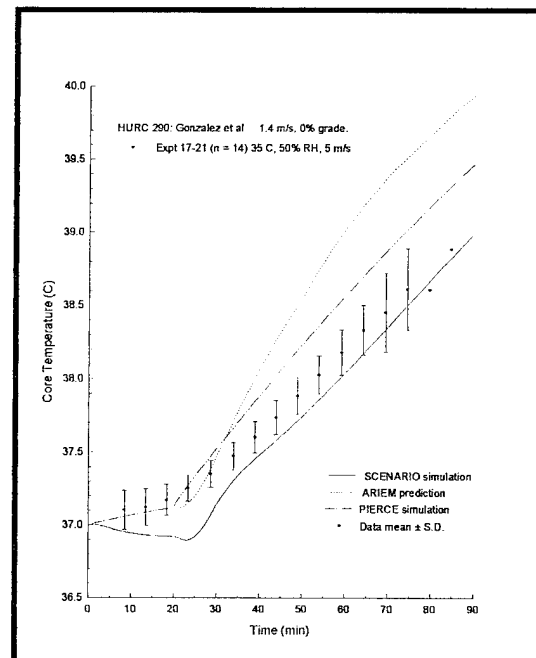


Figure 8. Fourteen unacclimated volunteers clothed in chemical protective clothing first rested then walked at $1.43\text{ m}\cdot\text{sec}^{-1}$ in a 35°C , 50% RH climate. ARIEM could only be programmed for the walking phase.

period, but SCENARIO was definitely closer during the 70 min working phase. ARIEM could not be programmed for this situation (a resting phase followed by a working phase); instead, the program output was offset by 20 min to correspond with the onset of exercise. As in all but one of the studies, ARIEM over-predicted the actual temperature rise by a large amount.

CONCLUSIONS AND RECOMMENDATIONS

Three modeling approaches termed ARIEM, PIERCE and SCENARIO have been defined for predicting certain physiological responses collectively known as heat strain. Data were assembled from recent ARIEM studies and studies from the literature. To provide an objective measure of the overall goodness-of-fit between predicted and observed values of body temperature, the average rmsd between data mean and predicted values was calculated and compared with the average sd of each data set. This quantitative analysis was supplemented by graphical inspection. A summary of the quantitative results is shown in Table I.

Table I. Ave data sds and rmsds between predicted and observed values of T_{cr} for three different heat strain models in six different studies				
Study I. D.	sd DATA	rmsd SCENARIO	rmsd PIERCE	rmsd ARIEM
Kraning & Gonzalez, 1991	± 0.17 (shorts)	± 0.19	± 0.11	± 0.39
Kraning & Gonzalez, 1991	± 0.23 (MOPP IV)	± 0.27	± 0.69	± 0.76
Pandolf et al., 1992	± 0.25	± 0.27	± 0.69	± 0.09
Gonzalez et al., 1978	± 0.15	± 0.17	± 0.22	± 0.63
Gonzalez et al., 1992	± 0.14	± 0.21	± 0.26	± 0.50
Santee & Matthew, 1992 (personal note)	± 0.28	± 0.53	---	± 1.23
AVERAGE	± 0.203	± 0.273	± 0.394	± 0.600

While these numbers reflect the overall average goodness-of-fit, this number is somewhat misleading because in four of five cases it is weighted by values from both the

early and late parts of the experiments. From a theoretical point of view, the ideal thermoregulatory model should accurately predict the entire time course of change in body temperature. However, from a practical point of view, there is little interest in the early part of the experiment and graphical inspection reveals that it is during this period that deviations of both PIERCE and ARIEM from the data mean tend to be smallest and of SCENARIO the largest. If the deviations had been calculated using only the final values (as they were in the study of Gonzalez *et al*, 1978), the differences between the models would appear much greater. In any event, based on these data, the performance of SCENARIO surpassed the performance of the other two models.

Finally, while the ultimate model will be useful for accurately predicting the time course of critical physiological responses, they will not in themselves predict tolerance time or performance degradation. Current doctrine assumes that the level of T_{re} alone is sufficient to determine tolerance time and casualty rates. However, the level of other critical variables, alone or in combination, may be important as well. Further research is recommended to determine more precisely the relationship between the levels of T_{re} , T_{sk} and HR on the one hand, and measures of performance and endurance time on the other hand. For this task a large amount of data will be required, and the P²NBC²/ARIEM database will be an excellent resource for future modeling tasks.

POTENTIAL SOURCES OF ERROR

Although models are usually blamed for differences in predicted values and observed physiological responses, it is often forgotten that the accuracy of any model can be no better than the accuracy in the measurement of the independent variables supplied to it. Thus, large errors can be introduced when the values of any input variables are estimated or assumed rather than measured.

Estimating Heat Production

Marching is an important field activity, and the metabolic rate achieved in this exertion is dependent upon a number of factors including speed, grade, body weight, body type, amount of weight carried, how weight is carried and terrain type. It is possible to measure metabolic rate in the field, but it is a difficult procedure, particularly during the

performance of complex tasks. As a result, this important input variable of heat production is often estimated from tables or mathematical algorithms (which are themselves mathematical models) rather than measured.

A comprehensive mathematical model was proposed by Pandolf and colleagues in 1977 that takes into account many of these factors:

$$M = 1.5Wt + 2.0(Wt + L)\left(\frac{L}{Wt}\right)^2 + \eta(Wt + L)(1.5[V_w]^2 + 0.3GV_w) \quad (\text{Eq. 22})$$

and

$$W_{ex} = 0.098G(Wt + L)V_w \quad (\text{Eq. 23})$$

where M is total energy expenditure (W), W_{ex} is external work (W), Wt is body weight (kg), L is clothing and equipment weight (kg), h is a "terrain multiplication factor" (nd), V_w is walking speed ($\text{m}\cdot\text{s}^{-1}$) and G is the grade of inclination (%).

Figure 9 shows averaged data from a study by Patton et al. in 1991 on burdened subjects walking on a level treadmill at three different speeds: 1.12, 1.34 and $1.61 \text{ m}\cdot\text{s}^{-1}$. Lines represent calculated values from Eq. 22 using averaged anthropometric data of the study subjects. Note that model estimates are always within one sd of the mean and usually much better. Estimates of the mean increased in accuracy as load was increased. When the load carried was only 5.2 kg, Eq. 22 consistently underestimated the average metabolic rate which indicates that it may contain a systematic and potentially correctable error. Compar-

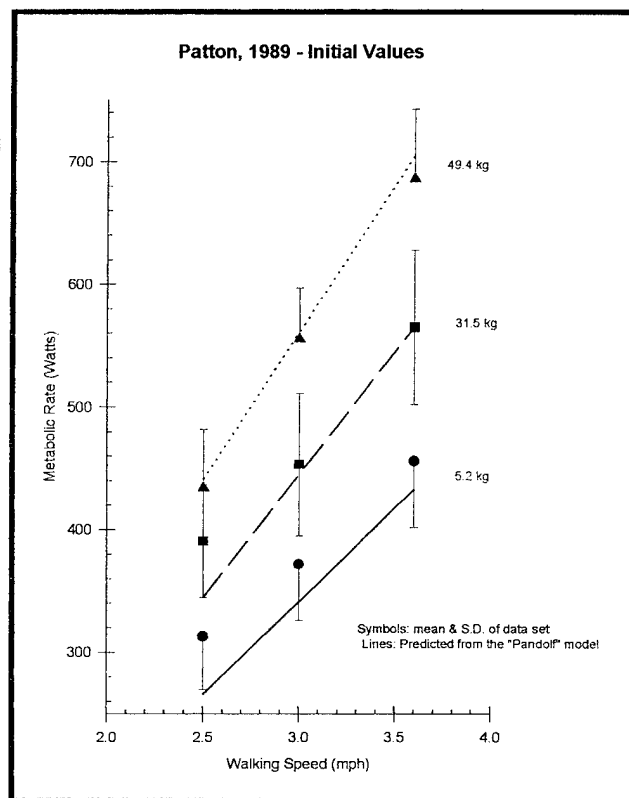


Figure 9. Data from Patton et al. Initial metabolic rates of burdened subject level-walking at different speeds and loads. Compared with predictions from Eq. 20.

ng the point at $1.61 \text{ m}\cdot\text{s}^{-1}$ and 5.2 kg with the point at $1.34 \text{ m}\cdot\text{s}^{-1}$ and 31.5 kg indicates that this error is probably related to the small load weight and not to the low energy expenditure, as the same energy expenditure was accurately predicted at the higher load, lower speed combination.

Table II. Difference between average initial (8-10 min) and average final (150-210 min) metabolic rate. Data of Patton *et al.*, 1991.

Load (kg)	Walking Speed ($\text{m}\cdot\text{sec}^{-1}$)		
	1.13	1.34	1.61
5.2	-1 W (-0.3%)	+5 W (+1.3%)	+2 W (+0.4%)
31.5	+8 W (+2.0%)	+45 W (+9.9%)	+56 W (+9.9%)
49.4	+51 W (+11.8%)	+82 W (+14.8%)	+128 W (+18.7%)

These estimates are based on initial values of metabolic rate, taken within the first 8-10 mins of work. At higher workloads there can be substantial increases in energy expenditure with time, as shown in Table II.

This long-term effect is minimal at the lowest walking speed when carrying any load, but advances with increased load carriage at the two faster walking speeds.

The long-term effect also appears to be slightly augmented by increasing speed, although the impact of speed is smaller than the impact of load.

The importance of accurately knowing energy expenditure when using any of the predictive models cannot be overemphasized, particularly when subjects are working at low to moderate intensities and wearing protective clothing. As can be seen from

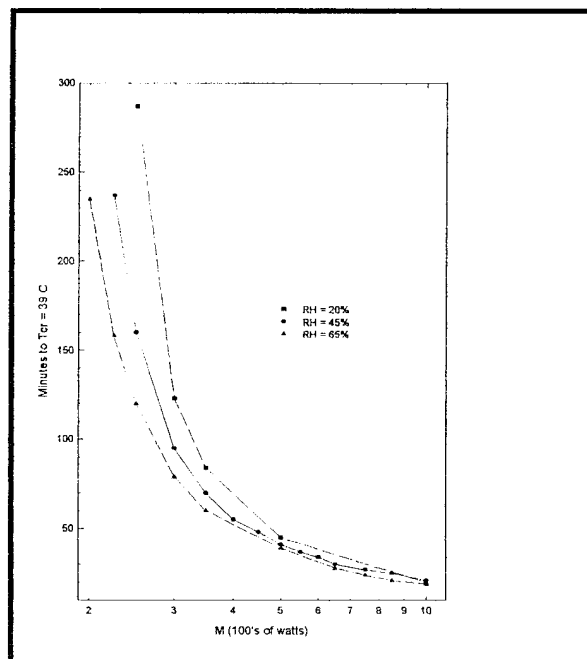


Figure 10. Predicted tolerance time as a function of metabolic rate and RH. DB temp. = 27°C , $V_{\text{air}} = 1.5 \text{ m/s}$, subjects in MOPP IV. Predictions with SCENARIO.

Figure 10, tolerance time under these conditions is an inverse non-linear function of energy expenditure. Predicted tolerance time changes fastest in the region below 400 W. Unfortunately this corresponds to the energy expenditure of most common tasks. Also the effect of other factors such as RH is greatest in this region. Therefore, it is extremely difficult to accurately predict tolerance time at low levels of stress. On the other hand, when subjects are performing heavy work, tolerance time changes slowly, even with large changes in energy expenditure. Since values nearly converge, it is not as urgent to accurately estimate energy consumption when workloads are very high.

Estimating Effects of Acclimation

It is well known that core temperature rise is moderated by acclimation to heat. Givoni and Goldman characterize this as a two step process: a reduction in resting core temperature and a lessening of the rise in temperature during work in the heat (Givoni and Goldman, 1973). In the ARIEM model Givoni implements these hypotheses with two equations:

$$\Delta T_{re0} = 0.5 \exp^{-0.3N} \quad (\text{Eq. 24})$$

and

$$\Delta T_{ref} = 1.2 \left[1 - \exp^{-0.5(T_{ref}-37.15)} \right] \exp^{0.3N}. \quad (\text{Eq. 25})$$

Combining Eq. 24 and Eq. 25 and adjusting for conditions where evaporation is limited, they write:

$$\Delta T_{ref_{accl}} = \exp^{0.3N} \left[0.5 + 1.2 \left\{ 1 - \exp^{-0.5(T_{ref}-37.15)} \right\} \right] \cdot [1 - \exp^{0.005E_{max}}] \quad (\text{Eq. 26})$$

As in the original equation, T_{ref} is approached by an exponential function of time:

$$\Delta T_{re}(t)_{accl} = \Delta T_{ref_{accl}} \left[1 - \exp^{(2-0.5\sqrt{\Delta T_{re}})\left(t-\frac{58}{M}\right)} \right] \quad (\text{Eq. 27})$$

where $\Delta T_{re} = (T_{ref} - T_{re0})$ and t = time in hours.

The effect of these equations on predicted T_{re} is shown in Figure 11. Subjects worked daily at 250 watts while acclimating in a 50° C environment wearing either BDU or BDU + BDO. Notice that the benefit of acclimation is less noticeable in BDU + BDO than in BDU alone because of greater evaporative restriction.

The direction and magnitude of changes generated by the acclimation algorithm generally correspond to our experiential model of this phenomenon; however, close

examination of the data used as the basis for Eqs. 24-26 suggests that further quantitative validation would be appropriate. This was also suggested by the validation data:

Estimating Blood Flow Distribution and Stroke Volume.

SCENARIO contains a elementary cardiovascular model for computing heart rate. This model is based on the following simplified relationships:

$$HR(t) = \frac{CO(t)}{SV(t)}$$

(Eq. 28)

$$SV(t) = f(\text{posture, activity, skin temperature})$$

(Eq. 29)

$$CO(t) = BF_{cr}(t) + BF_{mu}(t) + BF_{fat}(t) + BF_{vsk}(t)$$

(Eq. 30)

In this model, $CO(t)$ and $SV(t)$ are controlled and $HR(t)$ simply derives from these as a consequence. From a physiological point of view this is awkward logic as it ignores control of the nervous system on heart rate and the fact that the rate of flow through a tissue is not predetermined but arises as a consequence of local vasomotor

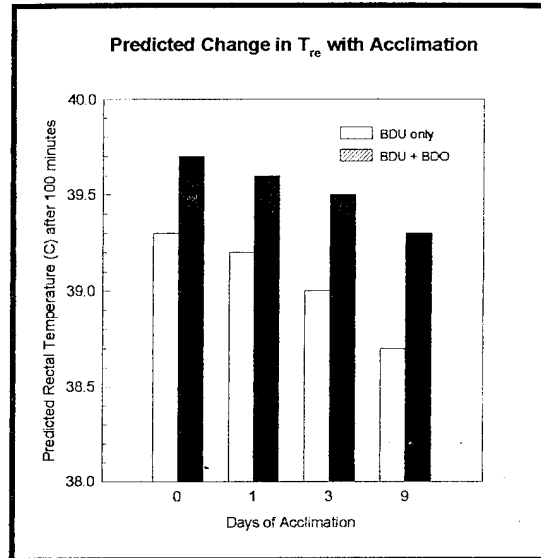


Figure 11. Changes in T_{re} after 100' of working in heat stress predicted by the Givoni acclimation algorithm in the ARIEM Heat Strain Model.

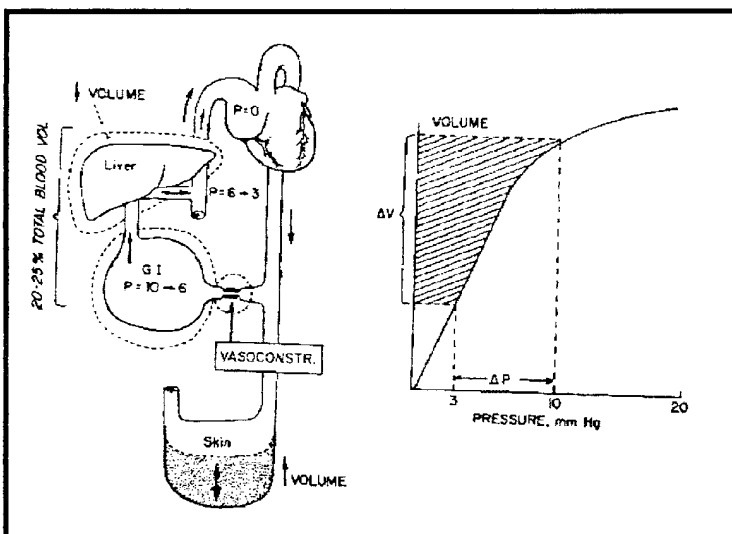


Figure 12. Illustration by Rowell of reciprocal actions of core vasoconstriction and skin vasodilation on passive blood volume shifts during heat stress. Blood is shifted from core to heart and lungs and translocated to skin. The effects of these volume shifts are modeled as reducing SV and increasing skin conductance.

activity and central pressure regulation (see Figure 12, from Rowell). Nevertheless, SCENARIO predictions of heart rate have been reasonable (see Table III). This is probably because the sequence of changes in pressure/perfusion relationships during exercise in heat stress are limited in number and reproducibly related to the external observable events. Internal validation is extremely difficult because of the paucity of quantitative data on distribution of blood flow and changes in skin blood volume and cardiac stroke volume during heat stress.

Table III. Comparison of heart rate predictability with data variance. Studies are described in text.

Study I. D.	sd Data.	rmsd SCENARIO
Kraning & Gonzalez, 1991	±3 bpm (shorts)	±7 bpm
Kraning & Gonzalez, 1991	±8 bpm (MOPP IV)	±9 bpm
Pandolf, 1992	±13 bpm	±19 bpm
Gonzalez et al. (1978)	±6 bpm	±6 bpm
AVERAGE	±7.5 bpm	±10.3 bpm

Needs for Future Research

Current military interest in heat strain models is based primarily (but not exclusively) on obtaining ways to predict survival rates of foot-soldiers performing front-line combat or emergency type tasks. A great deal of emphasis has been put on the foot-soldier to be his own vehicle and equipment carrier. That is why current validation studies, and even the planning for new ones, emphasize obtaining endurance data gathered from young, primarily male subjects, mostly physically fit and heat-acclimated, wearing worst-case uniform systems, performing extreme work in thermally extreme environments. In other words, today's models are based, primarily, on data obtained to determine the limits of male athletic performance under adverse conditions.

While it is important to predict endurance times of male soldiers at their performance maxima under the most extreme conditions, this is probably not the only condition

in which the soldier of the future is likely to be compromised. It may be more likely, as warfare rapidly becomes more automated, as the foot-soldier is equipped with more electronic apparatus, armor and other protective devices, and as the proportion of female foot-soldiers increases, that the breakdown of soldier systems during heat stress will relate more to an inability to perform critical duties at particular times than to outright physiological collapse.

In view of the paucity of data from female soldiers and of the need for models to predict performance deficits as well as endurance limits, research should be expanded into the following areas.

Gender Differences

There are few studies on heat stress in female soldiers and none which compare the physiological reasons for failure during heat stress in men and women. Besides accumulating "conventional" data on female soldiers, there are other questions of physiology and health in the female soldier during heat stress that need further study if more universal models are to evolve. Some of these questions, such as those relating thermoregulatory efficiency to the normal reproductive cycle and those relating evaporative cooling power to the production of sufficient sweat are obviously qualitatively different and uniquely related to gender. But another class of questions may turn up quantitative differences between males and females that ultimately may relate more to body size than to gender per se. These queries might include the size and responsiveness of the central blood volume and its ability to sustain a cardiac output responsive to the physiological needs of work in the heat, or the ability of the splanchnic circulation to displace blood centrally and maintain a cardiac stroke volume sufficient to prevent syncope. In the soldier's workplace yet a third class of questions may be important primarily to women or primarily to men simply because a particular task or set of duties by tradition may be assigned to either male or female soldiers.

Physiological Correlates of Psychological Deterioration

Measurement and prediction of physiological changes with models during heat stress offers the behavioral scientist an objective way to directly relate changes in measurements of performance with objective criteria about the subject's physiological state, thus increasing the generality of the observations. In other words, relating psychological

changes to physiological first principles increases the power of observations: it then becomes possible to interpolate between environments, uniform systems, work loads, etc. Despite the acknowledged importance of this approach, there seem to have been few studies where the design included equal emphasis on physiological and performance measures. Such studies must be emphasized to support modeling efforts in this area.

Modeling Militarily Relevant Tasks and Long Term Work

As noted earlier, most extant physiological data concerning responses to heat stress in an NBC environment were obtained on subjects while marching and bearing loads in backpacks. In this kind of work, large increases in heat production occur in large muscle groups of the legs and back. But there are other important field tasks in the NBC environment that require continuous and sustained activity of smaller upper-body muscle groups as well, such as those involved in transporting wounded, repetitive lifting and carrying tasks. Recently, these tasks been classified and their energy costs measured in males and females. There are no data, however, on the impact of heat stress on the physiological responses to such work. If we apply current heat strain models to work of this type, then we are forced to assume that physiological responses to increased heat production are independent of the type of work performed. This may not be true, especially when considering heart rate and related central cardiovascular responses. Further research is needed on the effects of hot environments on typical military tasks. One or two small but well-designed studies, specifically directed to this question, should give enough information to indicate whether or not future modeling efforts can ignore the specific task and focus only on total energy expenditure or whether a more complicated, task-specific approach should be taken.

We also have little research information on physiological responses to military tasks of long duration in hot climates because our data are principally derived from work of 2-4 hrs duration. Thus, while current models may predict that a safe steady-state physiologically compensable situation may exist in the short term (e.g., Figure 4), they may not be suitable for predicting long-term effects, where progressive dehydration, calorie depletion, diurnal phenomena and fatigue could eventually reverse the outcome. There is ample evidence from short-term experiments that manipulation of individual

factors -- dehydration, glycogen depletion, circadian shifts in body temperatures, etc. -- can affect thermoregulatory processes. Studies of longer time scale and of daily repetition of task effort should be conducted to determine how models need to be modified to include such effects.

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